Making the Relationships Visible: Testing Alternative Display Design Strategies for Teaching Principles of Hemodynamic Monitoring and Treatment

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A hemodynamic monitoring and control task was used to explore the utility of perceptually based displays to teach basic hemodynamic principles. The baseline display showed discrete values of key hemodynamic data elements. Alternative displays showed (a) anatomical relationships between those elements, and (b) causal constraints. Critical care nurses and student nurses used simulated "drugs" to correct simple hemodynamic disturbances using the three displays. Showing the anatomic constraints on pressure and flow improved treatment coordination by novices. Showing how etiological factors related to symptoms shortened the time required to reach a criterion level of performance and improved treatment coordination for both novices and experts.

INTRODUCTION

Over the past twenty years, sophisticated monitoring devices have become commonplace in critical care units and have proved beneficial in many ways. The new technology provides an observable window on what may be an otherwise unobservable state of the patient and allows clinicians to obtain rapid, frequent, repeated measures of physiological parameters so clinicians can detect potential problems before overt symptoms develop and titrate various drugs to maintain patient parameters within optimal ranges. But these innovations in critical care technology have also produced new problems [1]. Despite their many technological improvements, most monitoring devices still function as "single-sensor-single-indicator" devices [2]. That is, for each device used, a single variable is recorded. From the various data elements generated by independent sensors, clinicians must select and integrate those parameters relevant to the immediate situation. This results in sequential, piecemeal data gathering [3] that, in physiological monitoring tasks, precludes a more coherent understanding of the interrelationships of system functions and their underlying physiologic mechanisms [4].

Even though newer computer network-based monitoring systems are attempting to bring signals and alarms into a consistent format, they have not been able to solve what is essentially a multivariate analysis task for the clinician [5]. The clinician must still decide which information to use at a given time and how those variables relate. It is this task that educators teaching hemodynamic monitoring find most difficult for their students to learn.

The problem clinicians face can be understood as an example of the more general problem of perception. That is, how does an observer achieve the mapping of very many atomic elements into the perception of a chair, a sunny day, or an old friend? Similarly, how does the clinician as perceptual system achieve the mapping of very many atomic elements into a few categories of information? Given the equivalence of the clinical and perceptual problems, knowledge gained from the study of perception may be useful in creating displays that will be useful in teaching diagnosis and treatment.

One potentially useful concept is Gibson's characterization of information as higher-order invariants--patterns of persistence and change that structure the relevant medium in ways that are specific to the environmental facts they represent [6, 7]. For example, in vision, the source of information is the optic array which is structured by light reflecting off the various surfaces and substances that make up the environment. The transitions in the patterning of light are specific to the faces and facets of surfaces. Since this kind of structure is available to be perceived from the outset, it need not be added by the perceiver.

Additional support for this line of thinking comes from research on expertise. Studies of chess players [8, 9] have shown that experts rely heavily on their ability to detect familiar patterns. Clinicians too rely heavily on perception. Clinical experts easily detect the underlying structure of a previously experienced class of problems [10, 11]. Indeed, for experts, perception often precedes conception [10].

We have used Gibson's theory of direct perception to develop display designs that exploit perception by showing the inherent relationships between data elements. The purpose of this paper is to explore the utility of these displays as devices for teaching novices the complex relationships that underlie hemodyamic monitoring and treatment.

DESIGNING THE DISPLAYS

Traditionally, the inherent complexity of hemodynamic processes has seemed to demand one description for arterial hemodynamics, another for cardiac hemodynamics, etc. Overall descriptions are rarely seen. One exception is a well-known approach of Guyton [12], in which the major components of the hemodynamic system are treated as interconnected compartments in an effort to understand the more global relationships between pressures and flows. Guyton has developed a computer simulation which, in its most basic version, shows the intrinsic constraints on pressure. Arterial, venous, and atrial pressure and cardiac output are dependent variables, and fluid volume, contractility, and resistance are independent variables in the Guyton simulation.

The Guyton data were presented in three different visual formats: a traditional "strip-chart" display [5], an integrated balloon display, and an etiological potentials display. Drug controls are the same for all displays. Participants use six generic "drugs" to treat observed hemodynamic problems. Drugs act on the etiological factors--resistance, contractility, and volume. Participants select a drug and dose, then press a mouse button to give discrete "drug" doses.

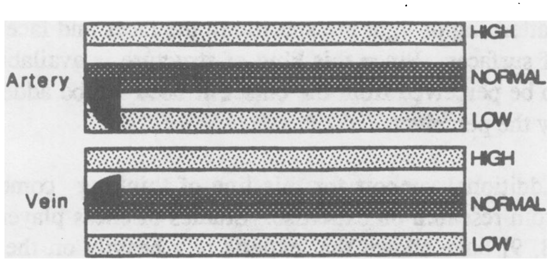

Figure 1. Arterial and venous pressures in TSD

In the traditional strip-chart display (TSD), arterial, venous, and atrial pressure, cardiac output, and resistance are shown as separate bar graphs (Figure 1). The vertical axis is color-coded for target range (green) and danger (red) regions. Values for each parameter are selected by sampling the Guyton simulation at one-second intervals.

The goal of the integrated balloon display (IBD) is to make visible the anatomical constraints on blood pressure and flow (Figure 2). By making the connectivity of the system visible, we hoped to teach participants to anticipate the effect of a change in one component, for example, a drop in right atrial pressure, on a subsequent change in another component, for example, cardiac output. The three pressures are shown as changes in the horizontal dimension of three ellipses (balloons). We have used the "balloon" image as a kinematic analog for the underlying dynamics of blood vessels, which have balloon-like characteristics [13]. The left ventricle is shown as a "bellows" to show the heart's forcing function on blood flow. Two parallel lines connect each compartment to the next. The connector between the arteries and capillary bed indicates changes in resistance by a change in the diameter of the distal end of the connection (a "funnel" metaphor). A bar graph shows overall system status (the mean of the standardized, absolute distances from normal for the four dependent variables).

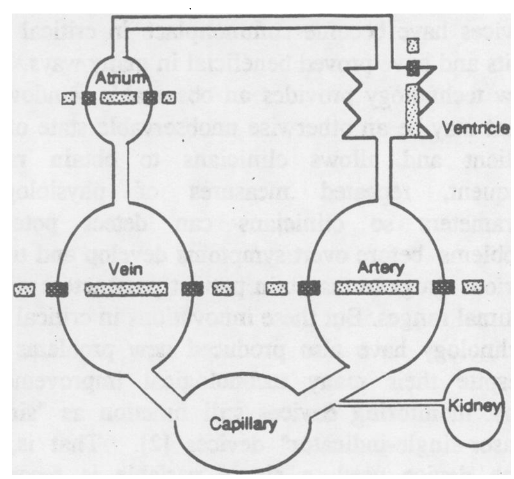

Figure 2. The integrated balloon display

Although the integrated balloon display shows how pressures and flows are constrained by their anatomical connections, it does not show how etiological factors in the model (fluid volume, resistance, and contractility) relate to changes in pressure and flow. Because the etiological components do not have a one-to-one relationship with pressure and flow, learning these relationships is not trivial. To make the relationships clear, a third (etiological potentials, or EPD) display was designed. In EPD, arterial, venous, and atrial pressure, and cardiac output are shown as vertices of a four-sided figure. When values are normal, the figure approximates a square and is located at the center of the window. The square can move in a two-dimensional (etiological) space defined by horizontal and vertical bars that cross at the center of the window. The vertical bar indicates contractility (heart strength); the horizontal axis shows resistance. Fluid changes are shown by an expanding or shrinking square.

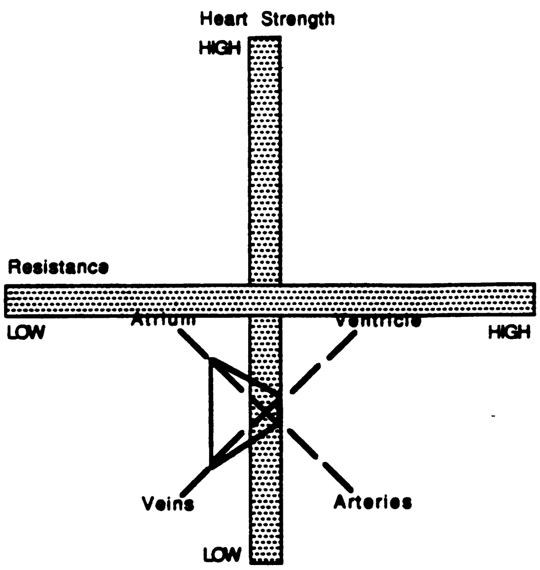

Figure 3. The etiological potentials display

In sum, the strip-chart display shows the values of three pressures and cardiac output as five separate graphs. Presumably, to coordinate treatment, the observer must already know, or must learn, how these discrete values relate. The integrated balloon display provides explicit information about how pressures and flow are connected anatomically. We assume that by seeing how anatomy constrains the values pressure and flow can take, the observer will be able to predict how a change in one will affect others. The etiological display attempts to make explicit how changes in etiological components relate to changes in pressure and flow.

The dynamic simulations were developed and presented on a Sun 4/260 workstation equipped with a 19 inch color monitor and Sun View graphics tools. Participants observed changes in pressure and flow that corresponded to certain disease states and corrected those states using the simulated drugs. To create a scenario ("illness"), the experimenter changes the value of any or all of the control parameters in the Guyton equations. In the experiment reported here, test scenarios were created in conjunction with clinical experts by varying three parameters (resistance, contractility, and fluid volume) to create "illnesses" such as high blood pressure, heart failure, or hypervolemia.

COMPARING THE DISPLAYS

We expected that learning to coordinate treatment quickly and accurately with the traditional strip-chart display (TSD) would be increasingly enhanced by the integrated balloon display (IBD) and the etiological potentials display (EPD) for all participants. However, because experienced critical care nurses are familiar with traditional displays, we expected that they would be able to use each display quite well. In contrast, we expected that student nurses would experience more difficulty learning to use the traditional strip-chart display (TSD) and show continued improvement with each succeeding enhancement (IBD and EPD).

Method

Participants. Six experienced critical care nurses currently enrolled as graduate students at the University of Connecticut School of Nursing served as the "expert" group. Critical care experience of this group ranged from 1-14 years with a mean of 6.17 years. The "novice" group was composed of six senior nursing students at the University of Connecticut.

Design and procedure. Three display types (TSD, IBD, and EPD) and three scenarios (low fluid, high resistance, and low contractility) were within-subjects variables in the mixed design. Participants were shown scenarios depicting common clinical problems and were asked to treat observed "illnesses" using the simulated "drugs."

Participants were given instructions that explained the purpose of the experiment, briefly explained hemodynamics, then described the three displays. The experimenter demonstrated changes participants might see the model undergo with each display. Participants then practiced using the drugs on each display (in a normal state) until comfortable with their use. In practice trials, participants were shown the same scenarios used in the test condition, but at different absolute values. Participants were required to solve each scenario with each display before beginning the experiment. In the test situation, each scenario was presented twice in each display condition. Presentation order of displays and scenarios was randomized.

Results

In addition to the number of practice trials required to solve each scenario using each of the displays, we recorded the number of scenarios solved in the test condition. Other performance measures, such as the time to initiate treatment, percentage of time in the target range, and number of drugs used have been reported elsewhere [14]. Finally, participants were asked to rank order the three displays for their usefulness as a teaching tool at three times during the experiment: after the initial instructions, after the practice trials, and at the end of the experiment.

Number of practice trials to criterion. The number of practice trials participants needed to solve each scenario once with each display ranged from one to six. A 2 (skill level) x 3 (display type) x 3 (scenario) ANOVA revealed, as predicted, a significant main effect of display type $F(2, 20) = 4.61$, $p < .05$. Participants required a mean of 1.63 trials to solve scenarios with TSD or IBD; but only 1.1 trials for EPD. In fact, for all but one subject (an expert), EPD resulted in one-trial learning. Experts required an average of 1.6 trials to solve each scenario with each display type; novices required an average of 1.4 trials. The ANOVA showed that this difference was not significant, $F < 1.0$.

Number of scenarios solved. In the test condition, experts performed very much as anticipated, solving 90% of the scenarios experienced with both TSD and IBD and 97% with EPD. As predicted, novices had more difficulty with TSD and improved significantly with each display enhancement. Novices solved 72% of the scenarios with TSD, 89% with IBD, and 100% with EPD (actually surpassing the experts). A 2 (skill level) x 3 (display type) x 3 (scenario) ANOVA showed that the display differences were significant, $F(2, 20) = 4.26$, $p < .03$. Skill level means (experts = 91.7% and novices = 87%) were ordered as predicted, but this difference was not significant, $F(1, 10) = 1.24$, $p > .10$.

Participant preferences. Participants were asked to rank order the three displays (a) for the purpose of instructing students about blood pressure and flow and (b) for the purpose of solving problems quickly. Experts consistently preferred the integrated balloon display as a teaching tool. Novices' opinions varied greatly and changed over time. Initially, three novices preferred IBD, two preferred EPD, and two preferred TSD. By the end of the experiment, five novices preferred IBD and two preferred TSD. EPD had become the second choice of five novices.

After trying each display, novices unanimously preferred EPD for solving problems. In contrast, experts' preferences varied. At the conclusion of the experiment, three preferred EPD, two preferred IBD, and one preferred TSD. Experts frequently related their preferences to their own learning style (e.g., whether or not they were a "visual" learner).

Discussion

In general, the results showed that the display types ordered as predicted and enhanced performance for novices more than for experts. IBD took as long as TSD to learn, but proved to be more useful--particularly for novices--in solving problems. EPD was easy to learn and more effective for all participants when solving problems.

Anecdotally, experts seemed to find EPD somewhat confusing. It seems likely, based on their comments, that they are accustomed to making a diagnosis based on preload, afterload, and contractility--with resistance at a different level of analysis. When the more available pressures and flows are immersed in the etiology space as an abstract object, experts may become rather disoriented. Even though problems can be solved simply by reducing the error in one of the three etiological dimensions (contractility, resistance, or fluid), some experts focused their attention on the changes in the shape of the "square."

When the context provided by the explicitly shown anatomical linkages in IBD was reduced to allow us to immerse pressure and flow measures into the etiology space, at least part of the semantics usually available to the expert was lost. Less familiar with that context, novices were not bothered by this loss. Consequently, they often performed as well as--or slightly better than--experts when using EPD.

IMPLICATIONS

Although we used a specific task domain (learning the fundamentals of hemodynamic monitoring and control) to test our approach to display design, our interest lies in identifying principles that can be generalized to the design of interfaces for a variety of educational--and practice--settings. Even in their current stage of development, the displays offer a useful alternative for enhancing hemodynamic monitoring training. Experts particularly liked having a tool they could use to play "What if?" by observing the effects of different drug combinations on pressure and flow. It is unlikely that any of the displays tested here will replace current critical care displays completely, in part because of the need to monitor accuracy of data produced by sensors. However, since the objective of the enhanced displays (IBD and EPD) is to show relationships, not specific values, it is hoped that what is learned with these displays will transfer to facilitate performance with more traditional displays.

The experiment reported here measured performance in a specific task. It did not attempt to ascertain exactly what subjects learned from each display (or from the experiment in general). Moreover, the extent to which what is learned with one display transfers to another remains an open question. Although the simulation we are using includes only the intrinsic constraints on hemodynamics, by using Guyton's more complex simulations, we can extend the displays to include other physiological constraints (baroreceptors, etc.) without changing the basic graphics. Our experimental task is admittedly simpler than hemodynamic monitoring in the "real world," so whether our results will generalize beyond this setting remains to be seen.

The results of the study suggest strongly that the learning and practice of complex diagnostic and treatment skills such as hemodynamic monitoring can be facilitated for experts, as well as for novices, when natural relationships or constraints are enhanced by a perceptually-based display. Showing the anatomic constraints on pressure and flow improved treatment coordination performance by novices. Showing how etiological factors related to symptoms shortened the time required to reach a criterion level of performance and improved performance for both novices and experts.

Acknowledgments

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